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Transient Refrigerant Migration and Oil Distribution of an R134a Automotive A/C System

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ABSTRACT

Automotive fixed orifice tube (FOT) systems are especially prone to cycling losses due to their clutch cycling operation. Therefore, it is important to better understand the dynamics of the refrigerant and oil migration during transient events such as cycling and start-up.

To measure the refrigerant mass and oil distribution of an automotive R134a FOT breadboard system, two ball valves around each component are added. By simultaneously closing the valves, the refrigerant and oil is trapped in different sections of the system and can be measured. The transient refrigerant migration during a stop-start transient as well as the refrigerant mass distribution as a function of system charge at steady state operation is presented. A transparent accumulator and transparent tubes at the inlet and outlet of the accumulator are used to visualize the flow of the refrigerant. High speed video snapshots are presented for the first seconds after the start-up. The oil distribution at steady state as a function of total refrigerant charge is presented. In addition, the entrainment ratio of the liquid refrigerant and oil mixture through the oil bleeding hole of the accumulator is determined.

INTRODUCTION

Refrigerant migration, redistribution and oil solubility have been identify as factors affecting the transient and cycling performance of all refrigeration and air conditioning equipment [1]. A key component of an automotive FOT system is the accumulator. Its primary function is to store excess refrigerant so that the system can operate under a variety of ambient conditions. The typical design of an accumulator for automotive applications consists of a vessel which has an inlet at the top and U-tube in the center with an opening close to the top of the accumulator. The U-tube dips down close to the bottom of the accumulator and then goes up and exits the accumulator. The idea behind this design is that liquid and vapor refrigerant phases are separated inside the vessel and that only the refrigerant vapor exits the accumulator. This prevents that liquid phase refrigerant can enter the compressor and potentially cause damage. However, since there is oil in circulation, an additional feature is necessary to guarantee that oil is returned to the compressor. For that reason the U-tube has a small opening at the bottom which allows entrainment of oil into the exiting vapor flow. For miscible refrigerant oil combinations, however, this entrained liquid will always be a mixture of oil and liquid phase refrigerant. It is therefore important to understand the relationship between the stored liquid refrigerant and oil in the accumulator and the entrainment since this is the mechanism by which oil is returned to the compressor

EXPERIMENTAL FACILITY

The experimental facility used for all experiments mentioned in this paper, consists of two environmental chambers as shown in Figure 1. The compressor is installed between the two chambers and is driven by a speed controlled electrical motor. A torque transducer in combination with a tachometer is used to determine the compressor power. The condenser is installed in an open-loop wind tunnel inside the condenser chamber. In the evaporator chamber the HVAC module containing the evaporator is attached to the wind tunnel and can therefore be considered part of the open-loop wind tunnel. The HVAC module flaps were set to fresh air intake for all experiments.

Before and after each heat exchanger, thermocouple grids consisting of welded Type-T thermocouples are used to determine the dry-bulb air temperatures. Air flow rates are determined by flow nozzles. The indoor and outdoor blowers exhaust the air directly into the chambers. An external R404A chiller system with the evaporator mounted on the ceiling inside the condenser chamber compensates for the heat rejected by the condenser. PID-controlled electric heaters are installed in both chambers to heat the room to the specified test conditions.

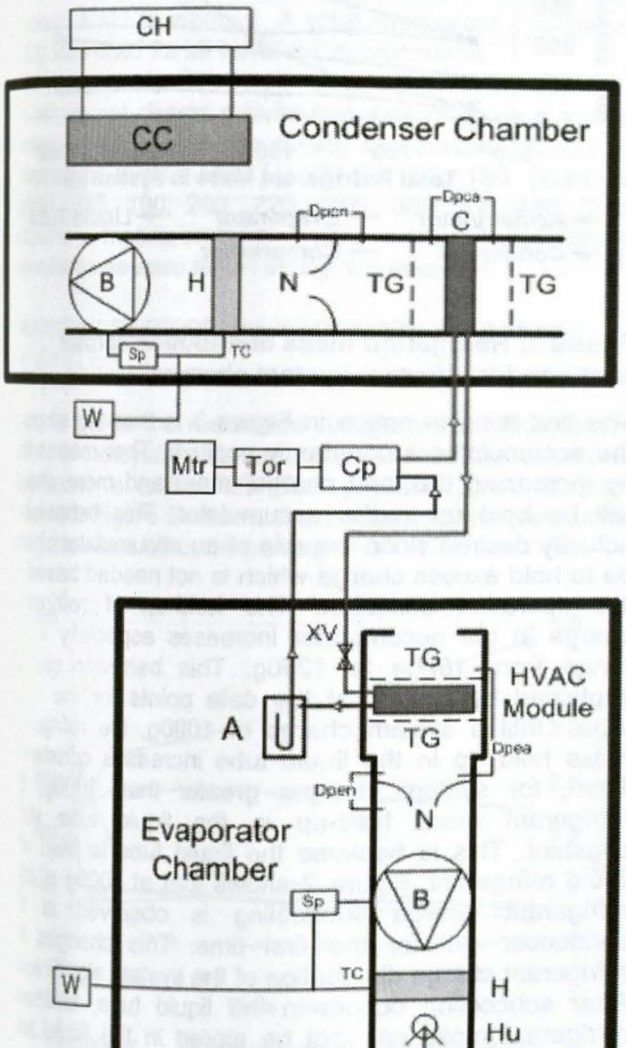

Figure 1. Experimental facility

A – Accumulator, **B** – Blower, **C** – Condenser, **CC** – Cooling Coil, **CH** – R404A Chiller, **Cp** – Compressor, Dp.. – Differential Air Pressure Transducer, **H** – Heater, Hu – Humidifier, **Mtr** – Motor, **N** – Nozzle, **Sp** – Speed Controller, TC – Temperature Controller, **TG** – Thermocouple Grid, **Tor** – Torque Transducer and Tachometer, **W** – Watt Transducer, **XV** – Expansion Device, Indices: **a** – Air, **c** – condenser, **e** – evaporator, n – Nozzle

The precision of the test facility is ±5% for the cooling capacity and the coefficient of performance (COP) for most steady state measurements [2].

SYSTEM DESCRIPTION

The system investigated in this study is a state of the art R134a automotive A/C system with a standard 0.072" internal diameter fixed orifice tube. The components were installed into the experimental facility with the same difference in vertical height as in the vehicle. In addition, ball valves were installed around each component. By closing these ball valves simultaneously, the refrigerant and oil masses were trapped in five sections: compressor, condenser, liquid tube, evaporator and accumulator. Ball valves were chosen because of their very low flow resistance. The ball valves were installed as close as possible around the components. The pipe lengths of the breadboard system were comparable to the original vehicle system with the exception of the liquid tube section. Due to the arrangement of the calorimetric chambers, the liquid tube for the breadboard system is 3.7 times longer than the liquid tube of the real vehicle system.

REFRIGERANT MASS MEASUREMENT METHOD

By closing the ball valves around each section simultaneously the refrigerant and oil masses are trapped in each section. To extract the refrigerant mass an evacuated sampling cylinder with known weight is connected to the section. After opening the valves between the sampling cylinder and the section, liquid nitrogen is used to cool the sampling cylinder. The chilled sampling cylinder stays connected to the section for 20 minutes, after which it is disconnected and heated to room temperature to avoid condensation of water vapor on its outside shell. The weight of the captured refrigerant is determined and the refrigerant is transferred from the sampling cylinder into a recovery cylinder. To determine if there was oil extracted from the section, the sampling cylinder is evacuated and weighed again, the weight this time being the extracted oil. This method is repeated twice for each section with exception of the accumulator section where this method is repeated three times. A comparison of the amount of refrigerant mass filled into the system to the amount of refrigerant mass recovered, shows that for 20 tests the difference is 8.5g on average less than the filled in refrigerant. This loss is primarily due to the refrigerant left in the hose after filling the system and minor amounts of refrigerant left in the hose when the refrigerant is recovered from the sampling cylinders. For a system charge greater then 850g, the uncertainty of how much refrigerant mass was actually in the system is less than 1%.

To ensure that the simultaneous closing of the ball valves was repeatable, three tests at steady state condition were performed. At the steady state condition, the refrigerant mass flow rate was 35g/s indicating that if the valves would be closed with a one-second delay, up to 35g of refrigerant could enter or leave each section. Table 1 shows the result of the three tests in units of percent of total refrigerant mass for a target system charge of 1250g when the ball valves were closed at steady state operating condition (see Table 4).

Table 1: Repeatability of refrigerant mass measurement method

	Exp. #1	Exp. #2	Exp. #3
Compressor	5.9%	5.0%	5.2%
Condenser	19.2%	18.9%	18.7%
Liquid Tube	27.5%	28.5%	27.1%
Evaporator	14.8%	15.8%	15.4%
Accumulator	32.6%	31.8%	33.6%

STEADY STATE DISTRIBUTION OF REFRIGERANT MASS

The refrigerant charge distribution across the five sections of the R134a FOT breadboard system was measured for different system charges at the operating condition (see Table 4). Figure 2 below shows the air side cooling capacity of the evaporator, the coefficient of performance (COP) which does not account for the fan power, the subcooling and superheat at the condenser and evaporator as a temperature difference. The temperature differences were calculated using the pressure and temperature measurements and comparing them to pure R134a property data at the corresponding saturation state.

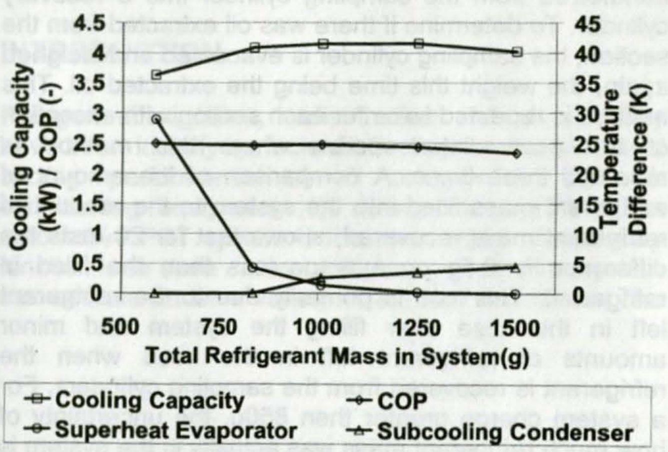

Figure 2: Cooling capacity, COP, subcooling and superheat for different system charges

As Figure 2 shows, there is an optimum in cooling capacity for refrigerant charges between 1000g and 1250g. For this range, the COP is almost constant, the subcooling increases and the superheat vanishes. From just considering these values, any refrigerant charge between 1000g and 1250g could be used. However, by considering Figure 3, which shows the refrigerant charge distribution across the components, further insight can be gained.

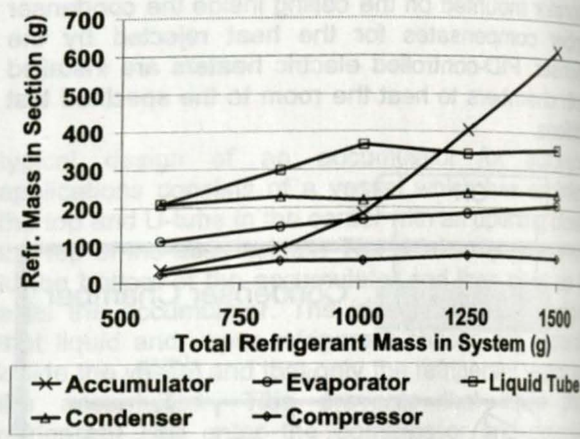

Figure 3: Refrigerant mass distribution across sections for different system charges

The first thing to notice in Figure 3 is that the slope of the accumulator is constantly positive. That means that by increasing the total charge, more and more charge will be held up in the accumulator. This behavior is actually desired since the role of an accumulator should be to hold excess charge which is not needed based on the operation condition. The hold-up of refrigerant charge in the accumulator increases especially in the range from 1000g to 1250g. This behavior can be explained by looking at the data points for the liquid tube. Until a system charge of 1000g, the refrigerant mass hold up in the liquid tube increases constantly. Then, for system charges greater than 1000g, the refrigerant mass hold-up in the liquid tube stays constant. This is because the liquid tube is filled with liquid refrigerant. Figure 2 shows that at 1000g of total refrigerant charge subcooling is observed at the condenser exit for the first time. This changes the refrigerant charge distribution of the system significantly. After subcooling occurs in the liquid tube, additional refrigerant mass can not be stored in the liquid tube because of the high density of the liquid refrigerant. In addition, the refrigerant mass hold up in the condenser is constant. For these reasons the refrigerant hold-up in the accumulator increases considerably. In absolute numbers, the refrigerant mass hold-up in the accumulator increases by 220g when the total charge is increased from 1000g to 1250g. This indicates that additional charge above 1000g is almost entirely stored in the accumulator. For the R134a FOT breadboard system 1000g is considered the optimum charge. This confirms the manufactures optimum charge of 700g for the vehicle system. The higher charge for the breadboard system results from the longer liquid tube.

TRANSIENT REFRIGERANT MASS MIGRATION

The refrigerant mass measurement method introduced in the previous section was used to determine the refrigerant mass migration for the R134a FOT breadboard system during a transient event. This event consists of an off cycle period in which the compressor is turned off for 3 minutes but the airflow rates at the heat exchangers are maintained, followed by a start-up when the compressor is turned on again. Due to the nature of the refrigerant mass measurement method the system needs to be recharged with refrigerant after each data point is taken. To ensure the system is at an identical steady state, the system is run for several hours at the conditions shown in Table 4 before the transient event is initiated. A total refrigerant charge of 1000g was used for all transient experiments.

The refrigerant charge distribution was measured at the following times in seconds during the transient event: 0 (compressor turned off), 5, 10, 20, 60, 180 (start-up begins), 185, 190, 200, 220, 240, 360 and 480. The pressure measurements and all temperature measurements were taken every 1.5 seconds.

TRANSIENT REFRIGERANT MIGRATION DURING OFF CYCLE

Figure 4 shows the measured refrigerant mass in each section of the system during the three minutes when the compressor is turned off. The pressure ratio is also presented. Figure 5 shows the measured temperatures during the same off cycle period.

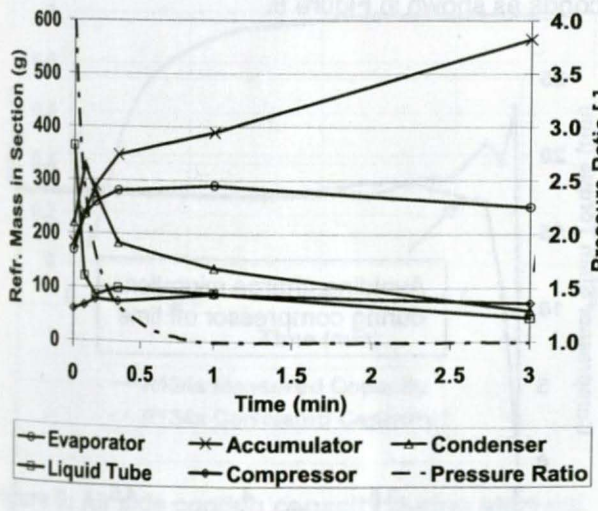

Figure 4: Refrigerant migration during off cycle

By inspecting the refrigerant mass migration in Figure 4 the conclusion is that the refrigerant migrates from the high-pressure components to the low-pressure components. At steady state, 58% of the total refrigerant mass in the system is found in the condenser and liquid tube sections. Three minutes after the compressor is stopped only 11% of the systems' refrigerant mass is found in those sections. The majority of the refrigerant mass migrates to the accumulator section, which holds 56% after three minutes compared to 18% of the total refrigerant mass at steady state.

The major driving force for mass migration during the first minute after the compressor is stopped is the pressure difference. The pressure in the condenser and liquid tube sections is much higher than the pressure in the evaporator and accumulator sections during the first seconds. In addition, at steady state, the refrigerant inside the liquid tube section is subcooled and therefore in the liquid phase. This leads to a significant refrigerant migration from the liquid tube through the fixed orifice tube into the evaporator and subsequently to the accumulator. However, Figure 4 shows that after 5 seconds, the refrigerant mass in the condenser increased. Since the refrigerant mass is increasing in every section during the first 5 seconds except in the liquid tube section, it can be argued that liquid refrigerant is flowing back from the liquid tube section to the condenser for a short period.

After one minute, the majority of the refrigerant mass migration has taken place. However, Figure 4 shows that between minute one and three refrigerant migrates from all components to the accumulator. Since the airflow rates are maintained at the heat exchangers, the lowest temperature in the whole system can be found in the accumulator during the off cycle. This leads to condensation of refrigerant vapor inside the accumulator and therefore to mass migration. It should be noted that if the system is turned off for a longer period of time, the compressor eventually will have the lowest temperature in a real system. This, of course, will lead to a redistribution of refrigerant charge.

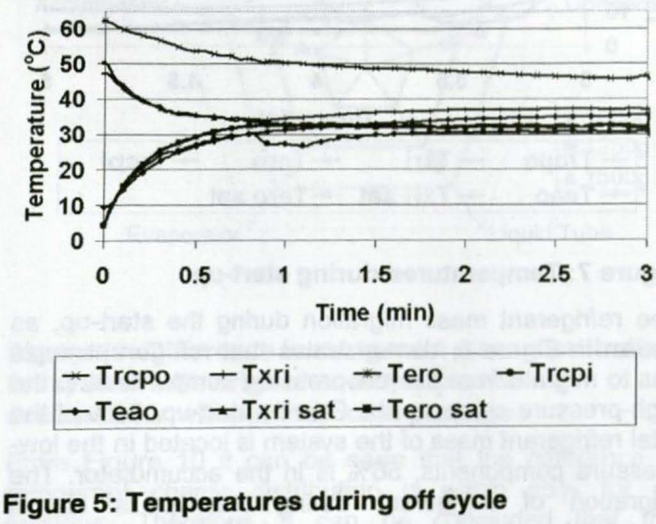

Figure 5: Temperatures during off cycle

Although the temperature of the refrigerant inside the accumulator was not measured, Figure 5 gives an indication that the temperature inside the accumulator is lower than the saturation temperature based on the measured pressure. After 50 seconds, the thermocouple reading at the suction side of the compressor inlet (Trcpi) drops by 4°C for a period of 20 seconds before it gradually increases again. From Figure 4 is can be seen that the refrigerant mass in the compressor reaches its highest value at 60 seconds. Therefore, this increase in refrigerant mass must come mainly from the accumulator. The visualization of the outlet tube of the accumulator (see Figure 12) confirms this assumption since the outlet is partially filled with liquid after three minutes.

TRANSIENT REFRIGERANT MIGRATION DURING START-UP

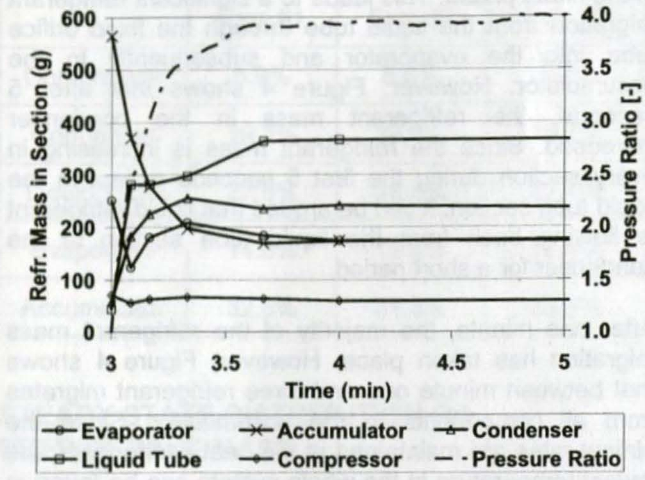

Figure 6: Refrigerant migration during start-up

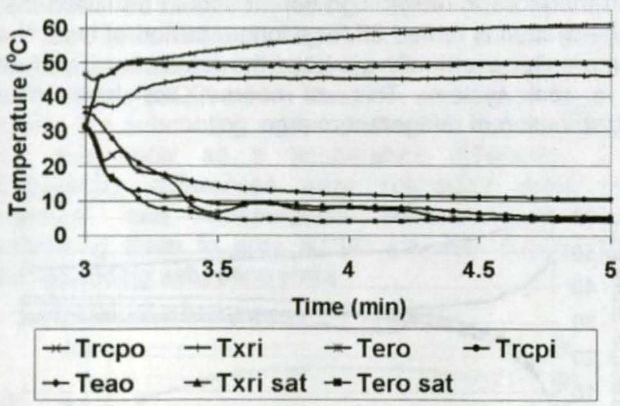

Figure 7: Temperatures during start-up

The refrigerant mass migration during the start-up, as shown in Figure 6, demonstrates that refrigerant mass has to migrate from the low-pressure components to the high-pressure components. Prior to start-up, 81% of the total refrigerant mass of the system is located in the low-pressure components, 56% is in the accumulator. The migration of refrigerant during start-up is almost completely achieved after one minute, at which time, 98% of the steady state airside cooling capacity is reached according to the data presented in Figure 9 which is presented in the next sub-section.

At the beginning of the start-up, the refrigerant mass in the evaporator section is decreased. This leads to a deficit of refrigerant mass inside the evaporator. The evaporator refrigerant exit temperature measurement (Tero) confirms this by showing a temperature higher than the saturation temperature (Tero sat) 5 seconds after start-up. The comparison between the temperature at the expansion device (FOT) inlet (Txri) and the saturation temperature based on the pressure measurement (Txri sat), indicates that after 5 seconds the refrigerant at the inlet of the fixed orifice tube is subcooled. The refrigerant mass in the evaporator increases after 5 seconds but the temperature measurement still indicates superheat at the evaporator outlet. The amount of refrigerant mass in the evaporator peaks 20 seconds after start-up, and at 30 seconds after start-up, the refrigerant exit temperature almost reaches saturation temperature. It increases again and eventually reaches saturation temperature 80 seconds after start-up. The air exit temperature of the evaporator (Teao) is not affected by this unsteady behavior and shows a smooth decline during the start-up.

Figure 6 shows that during the first 20 seconds 350g of refrigerant (that is 35% of the total refrigerant mass in the system) leave the accumulator. Figure 7 shows that between 5 and 20 seconds after start-up, the inlet temperature to the compressor (Trcpi) is lower than the refrigerant temperature at the evaporator exit (Tero) indicating that a significant amount of refrigerant is entering the compressor during this period. This leads to a high refrigerant density at the compressor inlet and explains why it is possible for the compressor to provide a high enough refrigerant mass flow rate to shift significant amounts of refrigerant mass within the first 20 seconds of the start-up. This, however, leads to increased compressor shaft torque during the first 20 seconds as shown in Figure 8.

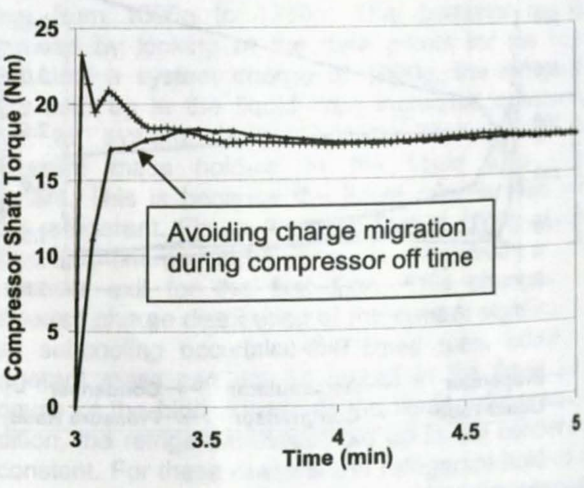

Figure 8: Compressor shaft torque during start-up

The peak in the compressor shaft torque is 32% higher then the torque at steady state condition. The peak in torque can be avoided by preventing the migration of refrigerant during the compressor off time by closing the ball valve upstream of the fixed orifice tube. This leads to a 28% reduction in compressor energy during the first 25 seconds of the start-up without loss in air side cooling capacity [3].

In conclusion, a major migration of refrigerant charge happens within the first 5 seconds of the start-up. Since the greatest charge migration happens at the accumulator a more detailed investigation is necessary which is presented in the next section.

CORRELATING AIR SIDE COOLING CAPACITY DURING START-UP

For the investigated R134a FOT breadboard system the following equation is used to represents the non-dimensional air side cooling capacity during start-up:

$$\frac{Q}{Q_{SS}}=\left(1-\frac{Q}{Q_{SS}}\bigg|_{t=0}\right)\left[\frac{1-\exp\left(-t/S_1\right)}{1+A\exp\left(-t/S_2\right)}\right]+\frac{Q}{Q_{SS}}\bigg|_{t=0} \quad (1)$$

In Equation (1) t is the time in minutes, Q is the air side cooling capacity as a function of time and Q_{SS} is the air side cooling capacity at steady state operating condition. The ratio between Q and Q_{SS} at time equals zero is the residual cooling capacity at start-up. To apply Equation (1) to a given set of data, two time constants, S1 and S2, and a constant A need to be determined. Table 2 shows the constants used in equation (1) to correlate the transient airside cooling capacity for the investigated R134a FOT breadboard system. Figure 9 shows both, the measured ratio of the air side cooling capacity to the steady state cooling capacity and the correlated ratio based on Equation (1) for the first two minutes of the start-up.

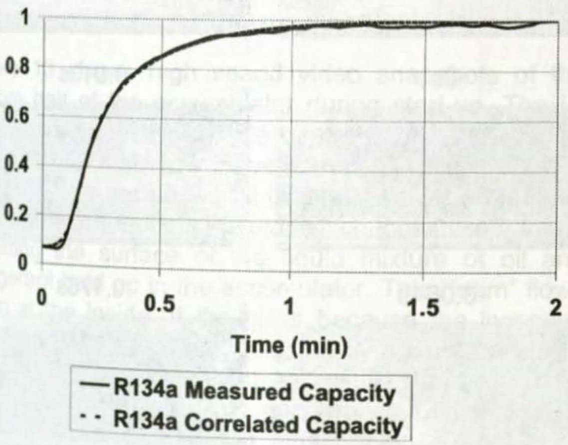

Figure 9: Air side cooling capacity during start-up

Table 2: Coefficients used in Equation (1)

Q/Q_{SS} at time = 0 [-]	0.070
S_1 [min]	0.2754
S_2 [min]	0.03425
A [-]	96.05

For the investigated start-up scenario the airside cooling capacity at start-up (t=0) is not 0 as shown in Figure 9. Therefore, a residual cooling capacity was present at start-up. In the presented case the residual air side cooling capacity was 7% of the steady state cooling capacity. As demonstrated in [3] equation (1) can also be used to curve-fit the air side cooling capacity of an R744 automotive system.

HIGH SPEED VISUALIZATION OF START-UP

The measurement of the refrigerant migration during start-up indicated that major migration of refrigerant charge happens within the first 5 seconds of the start-up. It also indicated that the greatest charge migration happens at the accumulator. To further explore the dynamic behavior of the refrigerant flow the original accumulator was replaced with a transparent accumulator. The transparent accumulator has the same design and dimensions as the original accumulator. To visualize the flow around the U-tube the desiccant package was removed from the transparent accumulator. To see if the desiccant package has an influence on the refrigerant distribution three experiments with three different system charges, 1000g, 1250g and 1500g were conducted. The systems were run at steady state condition (see Table 4) and the refrigerant mass distribution was measured. The spider chart shown in Figure 10 shows the difference in percent of the refrigerant mass distribution between the system with the original and the transparent accumulator without desiccant package.

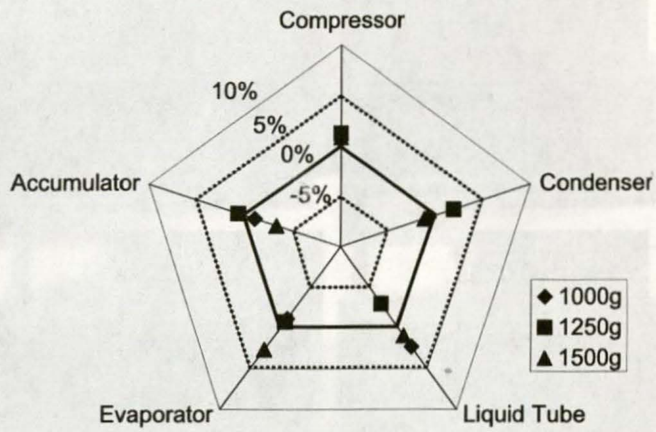

Figure 10: Difference in refrigerant mass distribution for system with original and transparent accumulator without desiccant package

From Figure 10 it can be seen that the difference in refrigerant charge distribution is within ±5% for all sections. Therefore, it can be concluded that the refrigerant mass distribution at steady state is not affected by using the transparent accumulator without desiccant package.

For visualizing the flow a Vision Research Phantom V4.2 high speed camera is used. To visualize the flow into and out off the accumulator, transparent tube sections with the same internal diameter as the original tubes were installed. They are installed directly at the inlet and outlet of the accumulator. High speed videos during the first seconds of the start-up were taken at the inlet, outlet and the accumulator. Snapshots of those videos are presented in Figures 11 to 13. For Figure 11 and Figure 12, which show snapshots of the inlet and outlet flow of the accumulator, the exposure time for each image is 4µs. For Figure 13, which shows snapshot of the bottom half of the accumulator, the exposure time is 2µs for each image. The procedure for the start-up is identical to the procedure described earlier. First the system is run at steady state for several hours. Then the compressor is stopped for three minutes. The time when the compressor is turned on again is referred to as time index 0 in Figures 11 to 13. A total refrigerant charge of 1000g was used.

VISUALIZATION OF INLET FLOW

Figure 11 shows high speed video snapshots of the accumulator inlet pipe flow during start-up. The flow direction is from left to right.

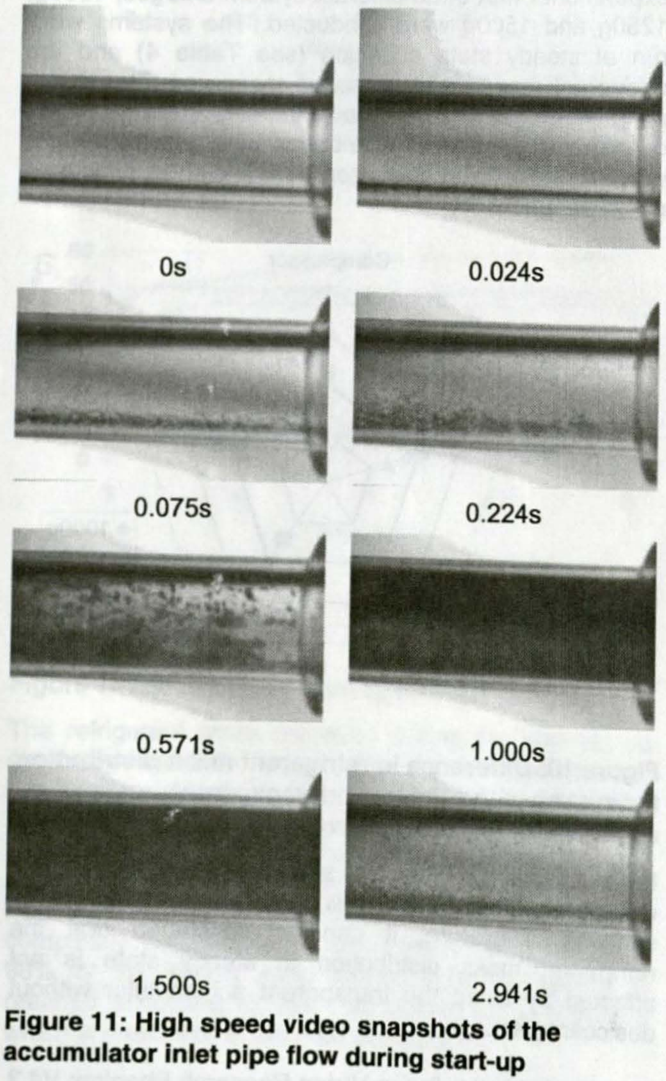

Figure 11: High speed video snapshots of the accumulator inlet pipe flow during start-up

After 0.024s the first signs of flow movement are visible in forms of ripples at the bottom of the tube. This also shows that there was a small amount of liquid held up in the tube before start-up. It should be noted that because of the miscibility of the refrigerant and oil a distinction between the two can not be made by visual inspection. Therefore, any liquid observed is most likely a mixture of liquid phase refrigerant and oil. From time index 0.024s until time index 0.571s a steady increase in entrained liquid droplets is observed. At time index 0.571s a sudden change occurs. A significant amount of liquid enters the accumulator. Within 0.05s after time index 0.571s the whole tube is filled with liquid droplets and vapor bubbles. As the snapshots at time index 1.000s and 1.500s show this mixture is optically dense. Between time index 1.500s and 2.941s the flow gradually reduces to the flow shown at time index 2.941s, where some entrained droplets are visible. Although the void fraction can not be determined from the video taken, it is apparent that a significant migration of mass in form of liquid occurs between time index 0.571s and 2.941s. This confirms the measurement in Figure 6 where a decrease in refrigerant mass in the evaporator was measured 5s after start-up.

VISUALIZATION OF OUTLET FLOW

Figure 12 shows high speed video snapshots of the accumulator outlet pipe flow during start-up. The flow direction is from left to right.

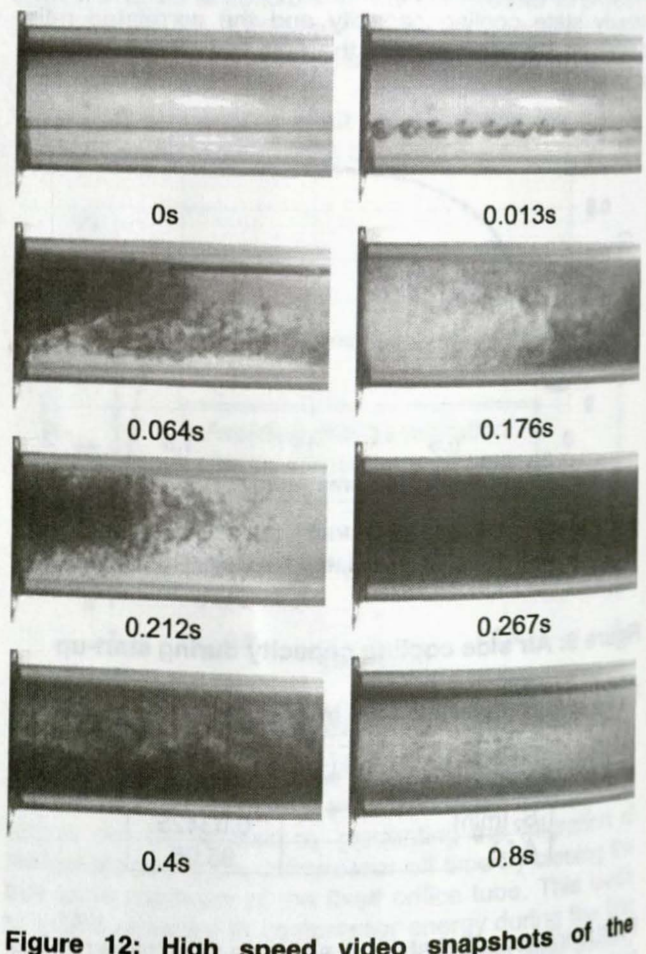

Figure 12: High speed video snapshots of the accumulator outlet pipe flow during start-up

At time index 0s, the bottom quarter of the outlet pipe is filled with liquid. This becomes even more apparent at time index 0.013s where the first signs of flow movement in forms of ripples are observed. At time index 0.064s a front of dense droplets enters and sweeps all the liquid with it. At time index 0.176s there is a small gap where it clearly can be seen that all liquid has been moved out of the tube section. At time index 0.212s a second front of dense liquid droplets enters. The density of the droplets decreases gradually as the snapshots at time index 0.4s and 0.8s show. The observation of the outlet flow of the accumulator leads to some very important conclusions. As described in the section "Transient Refrigerant Migration during off Cycle" there is evidence that refrigerant migrates from the accumulator towards but not into the compressor during the off-cycle period. This is confirmed by the snapshot at time index 0s where liquid hold up in the tube is visible. Furthermore, it seems that the U-tube is filled with liquid before start-up since a significant amount of liquid is observed at time index 0.064s after start-up. If this liquid would be entrained from the oil bleeding hole at the bottom of the U-tube, the resulting velocity at time index 0.064s would be 12 m/s with an acceleration of 186 m/s². However, by measuring the velocity of the fastest visible droplets at time index 0.064s reveals that the maximum velocity is ca. 4 m/s. From Figure 11 it can be seen that the front of dense liquid droplets can not originate from the inlet tube, e.g. by entering the top of the U-tube. This is supported by the fact that no significant amounts of liquid droplets are observed at the inlet until time index 0.571s. All the above observations lead to the conclusion that a significant amount of liquid is entering the compressor during the first seconds of start-up.

VISUALIZATION OF ACCUMULATOR

Figure 13 shows high speed video snapshots of the bottom half of the accumulator during start-up. The U-tube is visible in the middle of the accumulator. Until time index 0.7s no flow movement is visible. Then, first some droplets are observed falling down. At time index 1.0s a greater amount of liquid, which looks like a foam, is hitting the surface of the liquid mixture of oil and refrigerant held up in the accumulator. This "foam" flows down at the inside of the glass because the incoming flow from the inlet tube is deflected by a cone at the top of the accumulator. This explains while there is a time delay of 0.4s between the appearance of the droplet front in the inlet tube and the impact of those droplets on the surface of the liquid. Due to surface tension effects the liquid "sticks" to the shell surface. This is actually a desired effect to avoid that liquid droplets are entrained into the U-tube. However, as the snapshot at time index 2.0s indicates, the whole space above the liquid mixture of oil and refrigerant is filled with a "foamy" mixture of liquid and vapor. At time index 4.0s this "foam" eventually breaks down. Although it is not clearly visible in the snapshots, observation of the high speed video shows that it takes 1.8s until the there are visible signs that the liquid entering the accumulator penetrates all the way to the oil bleeding hole at the bottom of the accumulator.

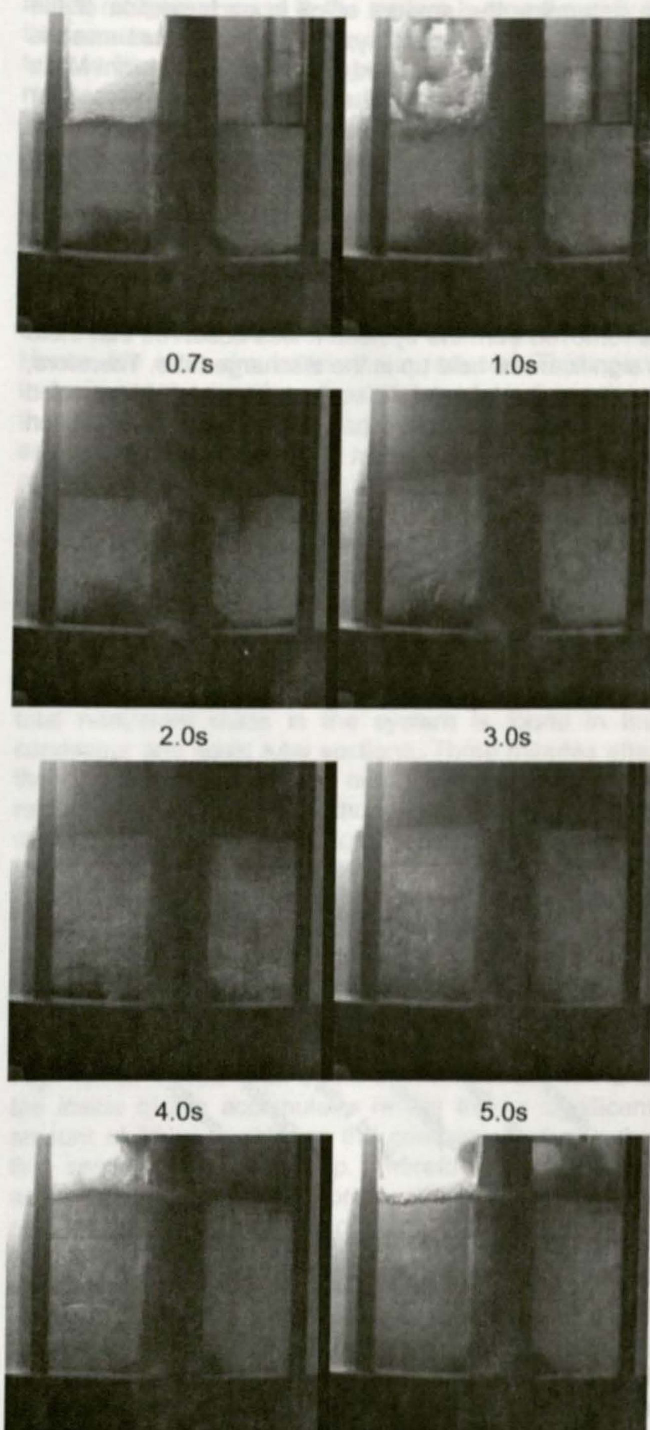

Figure 13: High speed video snapshots of the accumulator during start-up

OIL DISTRIBUTION AT STEADY STATE

The measurement of oil migration during start-up transient is an ongoing research effort and therefore data regarding the transient migration of oil within the system is not available at this time. However, data regarding the oil distribution at steady state operation is presented in this section.

To determine the amount of oil in each section of the R134a FOT breadboard system the refrigerant mass is first recovered as described in section "Refrigerant Mass Measurement Method". Then each section, except for the compressor itself, is flushed with liquid R134a using a commercial flushing device which separates the oil from the refrigerant after each flushing cycle. The flushing procedure is repeated three times for each section to insure that most of the oil is removed. The oil held up in the compressor is measured by weighing the compressor. For this procedure, the compressor has to be removed from the system. It was observed that there is significant oil hold up in the discharge tube. Therefore, the discharge tube was also flushed. It should be noted that the discharge tube is part of the compressor section regarding the measurement of refrigerant hold up.

Three experiments with three different system charges, 1000g, 1250g and 1500g were conducted for the system with the transparent accumulator without desiccant package. The system was run at steady state condition (see Table 4) and the refrigerant mass distribution (see Figure 3) was measured. The corresponding oil distributions are shown in Figure 14.

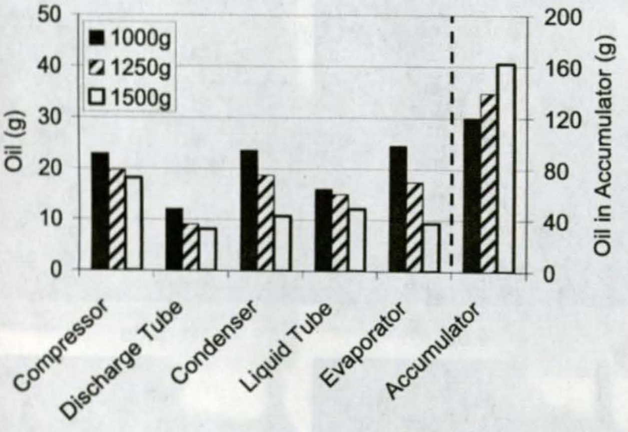

Figure 14: Oil distribution at steady state for different system refrigerant charges

The total amount of oil in the system for all experiments is 220g as recommended by the manufacturer. As Figure 14 shows more than 50% of the oil is found in the accumulator. As Figure 3 demonstrates, the amount of refrigerant hold up in the accumulator increases with increasing system charge. Figure 14 shows that the oil hold up in the accumulator increases with increasing refrigerant mass hold up. The consequence is a decreased amount of oil mass in all other sections including the compressor. The next subsection analyses the relationship between oil hold up in the accumulator and the oil in circulation ratio. This is accomplished by finding a mathematical relationship between the entrainment ratio, the oil in circulation ratio and the oil hold up in the accumulator.

DETERMINATION OF ENTRAINMENT RATIO

The following equations can be applied at the accumulator:

The oil in circulation ratio (OCR) can be expressed as:

$$OCR = \frac{M_{oil}}{M_{oil} + M_{ref}} \tag{2}$$

where M_{oil} is the mass of oil and M_{ref} is the mass of refrigerant in a given volume. The oil in circulation ratio at steady state operating conditions is assumed to be constant throughout the system. It is important to note that the OCR can only be determined for a volume in which there is no oil hold up. For the sections of the R134a FOT breadboard system this is only the case for the liquid tube section and only if the liquid tube is filled completely with a liquid refrigerant and oil mixture.

The concentration of the oil in the liquid mixture of oil and refrigerant in the accumulator ($C_{oil,accu}$) can be expressed as:

$$C_{oil,accu} = \frac{M_{oil}}{M_{oil} + M_{ref,liq}} \tag{3}$$

where $M_{ref,liq}$ is the mass of the refrigerant that is present in the liquid phase.

Since the accumulator has a U-tube with an oil bleeding hole at the bottom of the U-tube, a certain amount of the liquid refrigerant and oil mixture is entrained into the refrigerant vapor flow. This entrainment ratio (E) can be expressed as:

$$E = \frac{M_{oil} + M_{ref,liq}}{M_{oil} + M_{ref,liq} + M_{ref,vap}} \tag{4}$$

where $M_{ref,vap}$ is the mass of the refrigerant that is present in the vapor phase. The relationship between equations (2), (3) and (4) can then be expressed as:

$$E = \frac{OCR}{C_{oil,accu}} \tag{5}$$

To calculate the entrainment ratio for the three experiments with different system charges, 1000g, 1250g and 1500g the OCR is calculated based on the refrigerant and oil mass measured in the liquid tube section. For all three measurements the calculation of the refrigerant phase in the liquid tube based on saturation temperature and pressure indicated subcooled condition. Observation of the sight glass, installed in the liquid tube section, confirmed that only a liquid mixture of oil and refrigerant was present. To determine the concentration of the oil in the liquid mixture it is necessary to determine the amount of liquid phase refrigerant in the accumulator at steady state condition. A phase equilibrium calculation is performed for the accumulator volume at the measured pressure treating each species as a pure substance. This introduces a minor inaccuracy since the thermophysical properties of the liquid refrigerant and oil mixture are neglected. By applying equation (5) the entrainment ratio can then be calculated. The results are presented in Table 3.

Table 3: Entrainment ratio E

Charge	OCR	$C_{oil,accu}$	E
1000g	0.045	0.40	0.11
1250g	0.038	0.26	0.15
1500g	0.034	0.20	0.17

As Table 3 demonstrates, the entrainment of the liquid refrigerant and oil mixture through the oil bleeding hole in the U-tube of the accumulator increases with an increase in system charge. This is expected since the liquid height above the oil bleeding hole increases leading to a higher static pressure. The increase in refrigerant mass hold up in the accumulator is greater than the increase in oil mass hold up which leads to a reduction of the concentration ratio of oil to liquid refrigerant in the accumulator. The increase in entrainment is not high enough to compensate for this decrease in oil concentration leading to a reduction in the oil in circulation ratio. Since the overall mass flow rate is the same for all three experiments, this means that less oil is traveling through the compressor.

CONCLUSION

The presented experimental study focuses on an R134a FOT breadboard automotive air conditioning system. The refrigerant mass and oil distribution across the components as a function of system charge are presented. The transient refrigerant mass migration during a transient event is measured. In addition, high speed visualization of the inlet flow, outlet flow and the accumulator are presented.

The refrigerant mass measurement based on simultaneously closing ball valves to trap refrigerant mass in different section of the R134a FOT breadboard in combination with the liquid nitrogen recovery method, proved to be very accurate. For a system charge greater then 850g, the uncertainty of how much total refrigerant mass was actually in the system is less than 1%. The uncertainty regarding the determination of how much refrigerant is in each section is less then 2% in terms of total refrigerant mass in the system. In addition, the repeatability of this measurement method is demonstrated.

The presented data for the refrigerant mass distribution at steady state for different system charges shows that up to a certain charge, in the presented case 1000g, added refrigerant mass to the system is stored mainly in the accumulator and the liquid tube. When the liquid tube is filled with liquid refrigerant almost all additional refrigerant mass will then be stored in the accumulator. This, in turn, will affect the oil return to the compressor. As the data regarding the oil distribution shows, the increase in refrigerant mass hold up in the accumulator leads to a decrease of the concentration ratio of oil to liquid refrigerant. Although there is more entrainment of the liquid mixture of refrigerant and oil through the oil bleeding hole, this is not enough to compensate for the decrease in oil concentration in the liquid mixture. Hence, the oil in circulation rate is reduced. This needs to be recognized and accounted for when determining the amount of oil and refrigerant charge for a FOT automotive air conditioning system with a miscible refrigerant and oil combination to avoid compressor damage.

The presented data of the transient refrigerant charge migration during the investigated stop-start event shows that the refrigerant mass migrates from the high-pressure components to the low-pressure components during the off-cycle period. At steady state, 58% of the total refrigerant mass in the system is found in the condenser and liquid tube sections. Three minutes after the compressor is stopped only 11% of the systems' refrigerant mass is found in those sections. The majority of the refrigerant mass migrates to the accumulator section, which holds 56% after three minutes compared to 18% of the total refrigerant mass at steady state. The migration of refrigerant mass during start-up is almost completely achieved after one minute, at which time, 98% of the steady state airside cooling capacity is reached. However, a significant migration of refrigerant mass happens during the first 5 seconds of the start-up. High speed visualization of the inlet and outlet flow and the inside of the accumulator reveal that a significant amount of liquid is entering the compressor during the first seconds of the start-up. Therefore, although the accumulator is designed to prevent liquid transient from entering the compressor during operation, the current U-tube design does not prevent that liquid can enter the compressor during the first seconds of the start-up.

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APPENDIX

Table 4. Operating Condition

Comp.	Condenser		Evaporator		
Speed [RPM]	T [°C]	V [m³/s]	T [°C]	RH [%]	V [m³/s]
900	35	0.4583	35	dry	0.1358

T – Temperature, **V** – Volumetric Air Flow Rate, **RH** – Relative Humidity, dry means that dew point temperature was below refrigerant evaporation temperature